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Dissolved Phosphorus Export from an Animal Waste Impacted In-Stream Wetland: Response to Tropical Storm and Hurricane Disturbance

J. M. Novak,* A. A. Szogi, K. C. Stone, D. W. Watts, and M. H. Johnson

ABSTRACT

The ability of wetlands to retain P makes them an important landscape feature that buffers P movement. However, their P retention ability can be compromised through hydrologic disturbances caused by hurricanes and tropical storms (TS). This study had three objectives: (i) to determine the effects of hurricanes and TS on dissolved phosphorus (DP) concentrations and loads discharged from a Coastal Plain in-stream wetland (ISW); (ii) to evaluate shifts in P storage pools that would reflect P accretion/removal patterns; and (iii) to determine if relationships exist between storm characteristics with releases of DP and water volume. From January 1996 to October 1999, the ISW's outflow DP concentrations and flow volumes (Q) were measured and they were used to calculate DP mass export loads. In addition, the sediment total phosphorus (TP) concentrations were measured, and both the water column and sediment pore water DP concentrations were examined using passive samplers. In several instances, TS facilitated greater DP releases than a single hurricane event. The largest release of DP occurred in 1999 after Hurricanes Dennis, Floyd, and Irene. The large differences in DP exports among the storms were explained by Q variations. Storm activity also caused changes in sediment pore water DP and sediment TP concentrations. This study revealed that some TS events caused higher DP releases than a single hurricane; however, multiple hurricanes delivering heavy precipitation totals significantly increased DP export.

The high concentration of confined swine production in a limited geographic area of the southeastern North Carolina Coastal Plain region (Duplin and Sampson Co.) has caused concern about the long-term ability of soils in this area to assimilate P from manure (Kellogg et al., 2000; Mallin et al., 2002). Continuous manure application to fields has caused topsoil P concentrations to be in excess of typical row crop production requirements (Barker and Zublena, 1995; Kellogg et al., 2000; Novak et al., 2000). The buildup of excess topsoil P poses a significant management challenge as well as an environmental concern. Phosphorus movement into water resources is a major environmental issue because North Carolina River systems are highly susceptible to nutrient contamination (Kellogg, 2000).

Phosphorus movement via streams and rivers into coastal aquatic ecosystems in the southeastern USA region is buffered by wetlands (Reddy et al., 1999; Richardson, 1999). The buffering action arises from the wetland's ability to store P through sorption to sediments (Dosskey, 2001; Novak et al., 2004), in sediment pore water (Reddy et al., 1999; Novak et al., 2004), and through uptake by plants, periphyton, and microbial communities (Reddy et al., 1999; Richardson, 1999). However, P storage processes in wetlands can be disturbed by hydrologic turbulence from hurricanes and tropical storms (TS). For example, the extreme flooding caused by record-setting precipitation from multiple hurricanes in 1999 had acute effects on North Carolina coastal water quality. Many coastal bays and estuaries received elevated fluvial nutrient input loads that were linked to watersheds with intensive animal production (Bales, 2003; Shelby et al., 2005). Flooding in this region by Hurricanes Dennis, Floyd, and Irene over 36 d collectively increased P loads in the Tar River to 89% of the long-term mean annual P load into the nearby Pamlico and Neuse River estuaries (Bales, 2003). In these sensitive aquatic ecosystems, the large flush of nutrients and sediments, as well as changes in salinity, caused significant physical, chemical, and ecological disruptions (Paerl et al., 2001; Burkholder et al., 2004).

Hurricanes can differ in their rainfall delivery and residence time on making landfall, thus causing variations in their ecological disturbances (Bales, 2003). Sediment and nutrient discharge patterns from agriculturally intensive watersheds can vary substantially under different storm conditions. A single intense storm can be responsible for most or a large portion of the annual total nutrient and sediment losses (Gentry et al., 1998; Borah et al., 2003).

On one hand, a fast-moving hurricane can deliver precipitation on the coastal region that causes minimal disturbance to P storage processes in wetlands. On the other hand, high P export can occur when a slower moving unnamed storm, which does not qualify as a TS or a hurricane, deposits heavy precipitation that increases wetland outflows. In spite of their ecological importance as P buffers in the southeastern North Carolina Coastal Plain region, few studies have examined dissolved P (DP) export characteristics from an in-stream wetland (ISW) after storm events. We hypothesize that P released from an ISW can vary due to flow volume (Q) differences as a result of each storm's inherent precipitation amount and residence time over the mainland. This investigation had the following three objectives: (i) to determine the effects of hurricanes and TS on DP concentrations and loads discharged from an animal waste impacted Coastal Plain ISW; (ii) to evaluate shifts in the P storage pools that would reflect P accretion/removal patterns, and (iii) to determine if relationships

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677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: DP, dissolved phosphorus; FMS, fast-moving storms; ISW, in-stream wetland; TP, total phosphorus; TS, tropical storms.

exist between storm characteristics with the release of DP and Q from the wetland.

MATERIALS AND METHODS

Watershed and In-Stream Wetland Description

The studied ISW was located in the Herrings Marsh Run (HMR) watershed of Duplin County, North Carolina. This 2312-ha watershed is part of the Middle Coastal Plain physiographic region, which is underlain by sandy to clayey marine sediments (Daniels et al., 1999). The landscape is characterized by wide, nearly level to gently sloping upland areas that have been dissected by a network of primary, secondary, and tertiary black water streams (Daniels et al., 1999). Soils that formed in the upland areas are sandy and are somewhat poorly to excessively well drained. A typical upland soil series includes the Norfolk series (fine-loamy, kaolinitic, thermic Typic Kandiudult). Fairly wide (3 to 15 m) riparian zones form along the stream floodplain areas, which contain very poorly to poorly drained alluvial soils (Novak et al., 2003). Examples of soil series in the riparian zones include the Bibb (coarse-loamy, siliceous, active, acid, thermic Typic Fluvaquent) and Johnston (coarse-loamy, siliceous, active, acid, thermic Cumulic Humaquept). Daily precipitation totals were available from Warsaw [35° N, 78.03° W] and Clinton [35° N, 78.27° W] North Carolina (State Climate Office of North Carolina, 2004) and are presented in Fig. 1. Annual total precipitation measurements for the region during 1996, 1997, 1998, and 1999, respectively, were 1438, 1208, 1410, and 1854 mm.

The HMR watershed contains crop and animal production practices that are typical for the southeastern North Carolina Coastal Plain region (Novak et al., 2003). Liquid animal manure is typically applied to agricultural fields as a source of N and P fertilizer. Based on a 1993 animal inventory survey of the HMR watershed, the animal heads were estimated as 23 931 for swine, 94 000 for poultry, and 176 for cattle with an annual production of 120 Mg of manure P (Novak et al., 2003).

In-stream wetlands in the HMR watershed are commonly along the stream continuum in nearly level topographic positions or in open shallow depressions (Daniels et al., 1999). The ISWs can range in area from a few to several ha and are commonly bordered by deciduous trees (Bald Cyprus [*Taxodium distichum* L.], Swamp Chestnut Oak [*Quercus michauxii* Nutt.], Red Maple [*Acer rubrum* L.], Green Ash [*Faxinus pennsylvanica* Marsh.], and pines (Loblolly [*Pinua taeda*, L.] and Longleaf [*Pinus palustris*, L.]). A 3.3-ha ISW was identified in the north central part of the HMR watershed that received excess P due to leakage from a retired swine lagoon (Novak et al., 2003). The retired swine lagoon was located approximately 0.5 km upstream from the ISW. The ISW receives inflowing water from two shallow, second and third ordered black water streams on its eastern and western sides (Fig. 2). In 1994, the ISW was occupied by beavers (*Castor Canadensis*) that created and maintained a dam at the outlet. The beaver activity resulted in reduced stream outflows. The ISWs storage volume was 29 000 m^3, and the pond depth varied from <0.3 m in shallow regions to almost 2 m deep at the dam (Hunt et al., 1999).

Stream Sampling Locations and Stream Flow Measurements

Before 1996, both stream inlets flowed in well definable stream channels. During base flow, the channels were 2 to 3 m wide and between 0.3 and 0.5 m deep. Stream inflow rates at these locations were estimated using H-flumes (Free Flow, Omaha, NE) equipped with pressure transducers from 1993 to late 1994 (Hunt et al., 1999). In late 1994, the beavers improved the dam causing water elevation increases and flooding at both inlet locations. The flooding lasted for several months over 1995 and 1996; therefore, accurate stream inflow measurements were unavailable.

Flow discharge from the ISW was measured as outlined in Hunt et al. (1999). Briefly, a U.S. Geological Survey water flow measurement and water sampling station was located approximately 15 m downstream from the beaver dam. Daily estimates of mean water outflow volumes (Q, $m^3\ d^{-1}$) were then obtained electronically from the U.S. Geological Survey. Stream water flow was recorded at 15-min intervals using an automated water level recorder. Stream outflow samples were collected every 2 h using American Sigma automatic water samplers (Danaher Corp., Loveland, CO) and later combined to make composite 3.5-d samples.

Dissolved Phosphorus Measurements

Sample preservation was done by adding dilute H_2SO_4 to each automated water sampler bottle before sample collection. The acidified samples were collected weekly, filtered (0.45 μm), and analyzed for DP on a TRAACS AutoAnalyzer (BranLubbe, Elmsford, NY) using USEPA Method 365.1

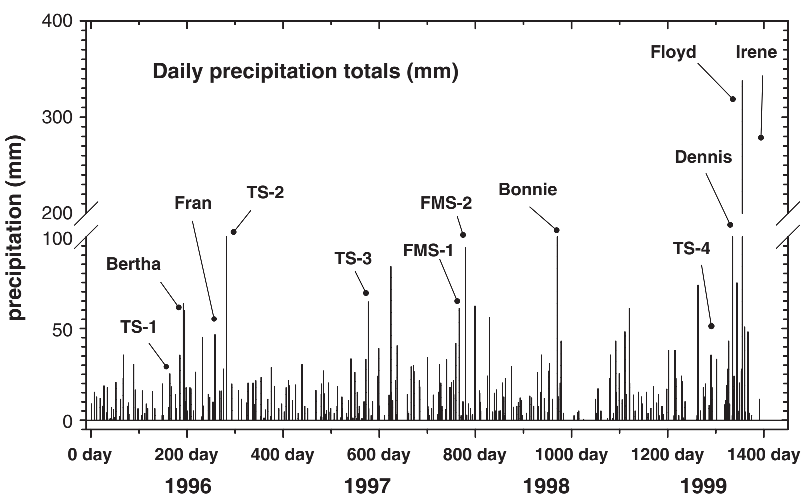

Fig. 1. Daily precipitation totals (1996 to 1999).

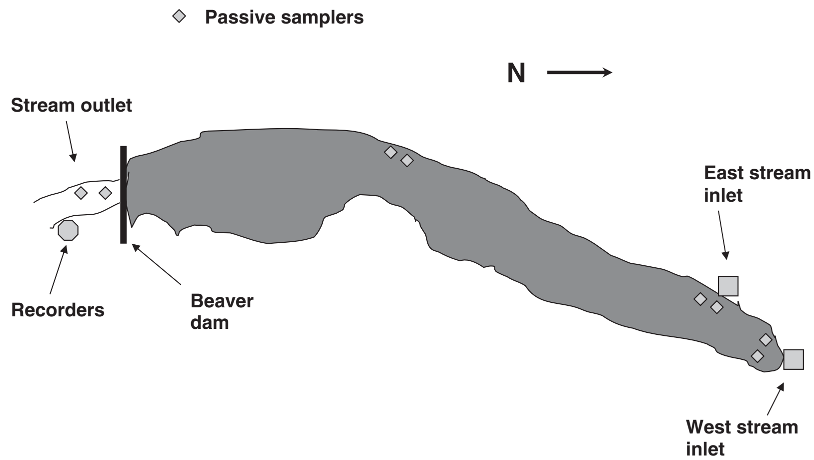

Fig. 2. Location of passive samplers, stream outflow recorder, and inflow sites.

(USEPA, 1983). The method's minimum detection limit was 7.5 μg L^{-1}. A value of 0 μg L^{-1} was assigned when a sample had a predicted DP concentration below the detection limit.

Wetland Outflow and Dissolved Phosphorus Mass Loads

From January 1996 to October 1999, daily outflow DP mass loads (kg d^{-1}) were calculated by multiplying the daily mean flows with DP concentrations determined from a composite sample. The DP concentrations were quantified in composite 3.5-d samples; estimates of continuous daily DP concentrations in outflows were made by linearly interpolating the DP concentrations over the 3- to 4-d intervals (Novak et al., 2004).

Passive Samplers, Sediment Collection, and Sediment Phosphorus Concentrations

Plexiglass passive samplers (peepers) were used once a year (during August or September in 1997, 1998, and 1999) to sample sediment pore water and the overlying water column according to procedures outlined in Novak et al. (2004). Specifically, the peepers were in place 6–20 Aug. 1997, which in this study was during TS-3. In 1998, they were in place from 2–16 September, which was less than 1 wk after Hurricane Bonnie. In 1999, they were in place from 1–14 September, which was 1 d after Hurricane Dennis. The peepers were located (Fig. 2) in a shallow zone (0.2 to 0.4 m deep) at the inlets, while the midpoint and outlet sites were located in deeper water depths (0.5 to 0.8 m deep). The peepers remained in the sediment for 2 wk to equilibrate with pore water and the overlying water column. After removing the peeper from the sediment, a plastic syringe was used to sample the compartment liquid. The liquid samples were acidified with dilute H_2SO_4 and analyzed for DP concentrations as described above.

Sediment cores (5 cm diam.) were collected to a 20-cm depth using a bucket auger at the same locations where the peepers were installed. Sediment samples were air-dried and ground to pass a 2-mm sieve. All sediment samples were extracted and quantified for TP as described in Novak and Watts (2004). The ISW accretion/removal patterns at the four sampling sites were determined by comparing relative differences in the annual sediment TP and sediment pore water DP concentrations.

Storm Activity Measurements

Hurricane and TS characteristics (dates making North Carolina Coastal contact, reported dates over Duplin County, and daily precipitation amounts), were gathered from the State Climate Office of North Carolina (2004) and NCDC (2006). Storm events that did not have hurricane or TS characteristics were classified as fast-moving storms (FMS). These FMS were defined as lasting less than 24 h as well as producing sizeable spikes in daily DP mass export values. Fast moving storms were identified using numbers and date of occurrence noted.

Statistics

Dissolved phosphorus concentrations in outflows were reported as monthly means. The daily DP mass loads exported along with daily stream Q values were summed to provide cumulative monthly and annual estimates. To determine if DP mass export and Q values varied as a function of year, the cumulative monthly Q and DP mass export estimates were plotted against the month of study. These curves were analyzed using linear regression, and the slope values per year of study were determined. A multiple comparison testing was used to determine significant differences among the four regression slopes (Zar, 1999). Although the cumulative Q and DP mass loads in 1999 were better fitted using an exponential model ($r^2 = 0.98$ and $P < 0.001$), the slopes for 1999 obtained through linear regression were used in the comparison. A Pearson product moment correlation was used to identify significant relationships among each storm's precipitation total with the ISW monthly outflow DP concentrations, Q, and DP mass export values. Between these variables only, the ISW monthly Q and DP mass export variables were significantly correlated ($r^2 = 0.9$; $P < 0.001$). These two variables were further analyzed using linear regression to predict DP export mass values with changing Q values.

The relationship between monthly DP mass released from the ISW after each storm to the percentage of annual total DP mass released for that year was examined using a hyperbola Eq. [1].

$$y = (a \times b)/(b + x) \quad [1]$$

In this equation, x = kg of DP released per month of storm, y = percentage of the total annual DP mass released, and a and b are equation variables. The relationship was initially examined using simple linear regression techniques, but the r^2 and P values were lower than values obtained with the hyperbola model. All statistical analyses were performed using SigmaStat software version 3.0 (SYSTAT, 2004).

RESULTS AND DISCUSSION

Storm Activity and Phosphorus Export Relationships

Storm activity during the 4 yr of this study varied greatly (Table 1). Outflow water characteristics also varied among the 4 yr; some of the most extreme monthly DP mass exported and Q values occurred in 1999. These extreme differences in water quality characteristics deserved examining the data on a yearly basis.

Year 1996

Storm events during 1996 had a major influence on DP behavior in the ISW. Two hurricanes and two TS were reported in Duplin Co. (Table 1). No major storm events occurred in the first 5 mo of 1996, and monthly precipitation totals were generally <80 mm (Fig. 1). During this same time period, monthly Q values ranged from 75 to 225 $\times$ 10^3 m^3 resulting in the ISW gradually releasing <14 kg mo^{-1} and culminating in a peak release of 26 kg in June (Fig. 3). Although the precipitation totals were fairly similar during these first 6 mo, the higher DP mass exported in June was the result of a spike in outflow. Tropical storm-1 lingered over the region from 11–14 June, but it only delivered 25 mm of precipitation. This tropical storm caused the Q to increase from 8000 m^3 d^{-1} to between 29 and 39 $\times$ 10^3 m^3 d^{-1} within a few days. The precipitation from TS-1 delivered in a 1-d period caused a monthly cumulative outflow volume of 219 $\times$ 10^3 m^3 and a release of 27 kg of DP (Table 1).

The first hurricane of 1996 was Bertha, which over 2 d deposited a combined 88 mm of precipitation. As a result of this hurricane, monthly outflow from the ISW was 127 $\times$ 10^3 m^3 mo^{-1} releasing 24 kg of DP from the ISW (Table 1). Compared with results after TS-1, Q and DP mass export were lower; this may be due to Hurricane Bertha causing relatively lower disturbance inside the ISW because its precipitation was deposited over a 2-d span.

In early September 1996, Fran was the second hurricane recorded in Duplin Co. This hurricane alone contributed 200 mm of precipitation to the high monthly total of 330 mm (Fig. 1). Unfortunately, the effects of Hurricane Fran on DP mass export could not be addressed because of equipment damage to the outflow recorder. As a result of recorder damage, no outflow measurements were available from 6–19 September. Yet, the second highest mean monthly DP concentration in Q during 1996 occurred after this hurricane (Fig. 3, 232 μg L^{-1}).

Tropical storm-2 was the last storm of 1996 to be reported in Duplin Co. It passed over the watershed on 8 October and delivered 135 mm of precipitation. Consequently, it created a large outflow pulse with Q from 9 to 73 $\times$ 10^3 m^3 d^{-1} measured from 8–13 October. Discharging 73 $\times$ 10^3 m^3 of water in 1 d meant that the ISW storage volume was recycled over 2.5 times. This high turnover volume of water contributed to a large increase in the total monthly Q (317 $\times$ 10^3 m^3 mt^{-1}). Therefore, DP released after TS-2 (57 kg) was much higher when compared with the other storms in 1996 (Table 1). This mass of DP exported from the ISW after TS-2 represented 27% of the annual DP mass load (206 kg). This mass was almost twofold higher than DP export percentages associated with TS-1 and Hurricane Bertha. This finding supports the argument that disturbances from hurricane events may not necessarily result in the larger P export amounts.

Year 1997

During the first 6 mo of 1997, daily precipitation totals were less that 40 mm (Fig. 1). Monthly Q values gradually declined from the ISW, and monthly DP mass export amounts were <25 kg (Fig. 3). Only in April was the DP mass export >25 kg due to the higher mean monthly outflow DP concentration (Fig. 3, 367 μg L^{-1}).

During the last 6 mo of 1997, there were a few spikes in daily precipitation amounts that were between 75 and 90 mm. During this same time span, there were a few monthly spikes in DP mass export and outflow DP concentrations. This was particularly evident from 19–22 August, when TS-3 deposited 70 mm of total precipitation (Fig. 1). A day before this storm, Q was 872 m^3 d^{-1}. During the 3 d following TS-3, Q increased from 2.5 to 9.7 $\times$ 10^3 m^3 d^{-1}. This storm caused severe disturbance to internal DP storage processes resulting in

Table 1. Precipitation totals and outflow water characteristics from the ISW after storm activity (TS, tropical storm).

Mo/yr	TS/hurricane	Precipitation†	DP outflow§	Q $\times$ 10^3¶	DP mass¶	DP mass as a percentage of annual load
		mm	μg L^{-1}	m^3 mo^{-1}	kg mo^{-1}	
06/96	TS-1	25	130	219	27	13
07/96	Bertha	88	175	127	24	12
09/96	Fran	200‡	232	108	28#	13
10/96	TS-2	135	149	317	57	27
08/97	TS-3	70	1389	86	117	29
08/98	Bonnie	183	298	145	48	9
07/99	TS-4	76	577	762	440	26
08/99	Dennis	166	284	327	23#	–
09/99	Floyd	392	231	2517	610	36
10/99	Irene	48	175	2839	509	30

† Precipitation totals recorded at Warsaw, NC.
‡ Precipitation total recorded at Clinton, NC.
§ Mean value for the month in which storm occurred.
¶ Cumulative value for the month in which storm occurred.
# Dissolved phosphorus (DP) mass estimates are low due to equipment damage.

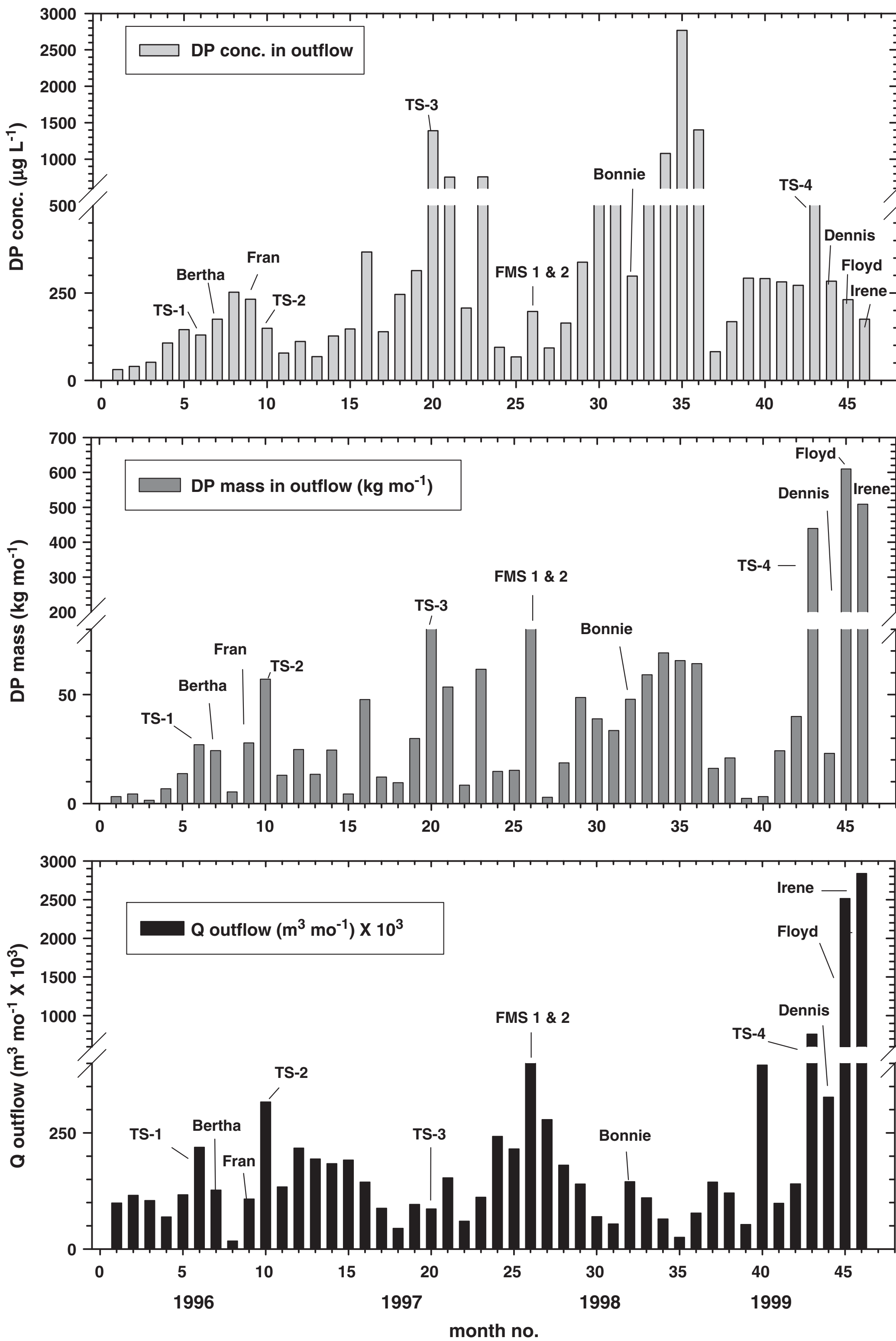

Fig. 3. Mean monthly dissolved phosphorus (DP) concentrations, monthly cumulative DP mass, and outflow Q values.

an increase in daily outflow DP concentrations between 90 and 3330 µg L^{-1}. As a result of the heightened outflows and DP concentrations, about 56 kg of DP was exported from 21–23 August. For the remainder of August, the ISW continued having very high mean outflow DP concentrations (90 to 3260 µg L^{-1}), which contributed to the release of 117 kg of DP. This tropical storm accounted for 29% of the annual release of 397 kg and repeats the finding that sizeable releases of DP can occur due to a single storm event (Table 1).

Year 1998

During this year, only Hurricane Bonnie occurred over the watershed (Table 1). However, two FMS occurred during February. One storm event occurred on 4 February (FMS-1, 766th day of study) and delivered 61 mm of precipitation, whereas the second one occurred on 17 February (FMS-2, 779th day of study) and deposited 94 mm of precipitation (Fig. 1). These storm characteristics caused spikes in daily Q (between 12 and 132×10^3 m^3 d^{-1}) resulting in DP releases of 29.2 and 22.1 kg, respectively, during 4 and 7 February and from 17–19 February. The combined mass of these DP releases represents 59% of the February total DP export of 87 kg (Fig. 3). This spike in DP export was related to the ISW being flushed multiple times in a short period of time. These flushing cycles created internal hydrologic turbulence that enriched the water column with DP because the daily outflow DP concentrations increased from 91 to as high as 731 μg L^{-1}. Hydrologic disturbances from the two FMS caused spikes in DP export values as large as some TS or hurricanes.

In spite of the fairly high daily precipitation totals, Q from the ISW decreased during April to July of 1998. During this time, the monthly DP mass export loads were between 30 and 50 kg. Composite samples collected from April to July contained monthly mean DP concentrations between 200 and 600 μg L^{-1} (Fig. 3) indicating that the outflow water was DP enriched. The increase in water column DP concentration and large daily outflows (1.7 to 4.9×10^3 m^3 d^{-1}) during this period facilitated the export of almost 150 kg of DP (April to July).

Hurricane Bonnie occurred from 27–30 August and delivered 183 mm of precipitation (Table 1). Before this hurricane, Q on the 25th was <800 m^3 d^{-1}, which increased from 15 to 51×10^3 m^3 d^{-1} during the 26th and 28th. Disturbances from Hurricane Bonnie caused the ISW during August to release a total of 145×10^3 m^3 and 48 kg of DP. The ISW released its highest daily DP mass exported (17.9 kg) value on the same day that the maximum Q value (51×10^3 m^3 d^{-1}) was recorded. This fact implies that the ISW in a 1-d period was flushed with almost twofold volumes of water. Similar to earlier examples, multiple flushing of the ISW storage volume caused internal hydrologic disturbances resulting in higher outflow DP concentrations and DP mass exports. These facts were supported by measuring 348 to 287 μg DP L^{-1}, respectively, in outflow 24 to 96 h after Bonnie departed the region. About 2 wk after Hurricane Bonnie, outflow DP concentrations decreased to 148 μg L^{-1}. This hurricane delivered more precipitation (183 mm) than the two FMS in February; however, it did not cause the highest monthly DP export from the ISW during 1998 (Fig. 3).

During the last 4 mo of 1998, monthly total DP mass export remained above 59 kg in spite of the sparse daily precipitation totals (Fig. 1, <45 mm from Day 974 to 1097) and cumulative monthly Q between 25.3 and 110×10^3 m^3 mt^{-1} (Fig. 3). The continued release of a fair amount of DP during this period was attributed to the highly enriched outflow DP concentrations (Fig. 3). In fact, the highest monthly mean DP concentrations in the outflow during the entire study happened during November 1998 (2768 μg L^{-1}).

Year 1999

This year was characterized by the most dramatic fluctuations in DP measurements in the ISW outflows (Fig. 3 and Table 1). Through the first 6 mo of 1999, the release of DP and Q were minimal, which was due to the low daily precipitation totals (<60 mm, from Days 1097 to 1247, Fig. 1). However, DP export patterns changed greatly after a series of storms from 12–15 July, collectively referred to as TS-4, which delivered 76 mm of precipitation (Fig. 1, Table 1). Although this precipitation total is comparatively smaller than other storms in this study, the effect was extraordinary on DP release. For instance, the hydrograph indicated that base flow conditions 1 d before TS-4 were 2×10^3 m^3 d^{-1}, which caused only 1.9 kg d^{-1} of DP export. In contrast, the precipitation from TS-4 delivered over 3 d caused a Q increase from 2 to between 24.5 and 46.5×10^3 m^3 d^{-1}. This spike in Q disturbed P storage processes resulted in 106 kg DP export. Similar to two previous examples, the high daily Q volumes flushed the ISW multiple times resulting in a huge mass of DP exported.

The Q remained from 39 to 49×10^3 m^3 d^{-1} for 9 d after TS-4 ceased. Later, on 25 July, a single storm event deposited 33 mm of additional precipitation. Drainage into the ISW increased Q to 61×10^3 m^3 d^{-1}. For 3 d after this small storm ceased, an additional 102 kg of DP was exported. By 30 July, the Q decreased to base flow conditions with 1.8×10^3 m^3 d^{-1} and 0.70 kg d^{-1} of DP was released. What was extraordinary about this activity was that from 12–28 July, sufficient water was discharged from the ISW (total 672×10^3 m^3) to infer that it was flushed at least 23-fold. From 12–28 July, 376 kg of DP was exported from the ISW, which represents a staggering 85% of the monthly mass export total (440 kg). More importantly, storms during July perturbed DP storage to such an extent that 440 kg of DP was exported, which represents 26% of the 1999 cumulative DP mass export amount (1688 kg).

During August 1999, Hurricane Dennis caused lapses in stream sample collection because of equipment malfunctions resulting in an inaccurate estimate of the August DP mass export (23 kg, Fig. 3 and Table 1). The flow recorders were not operational between 19 August and 7 September, so readings were lost for 3 wk. The equipment was functional before Hurricane Floyd delivered a devastating 24-h precipitation amount (392 mm) on 16 September. This large precipitation total resulted in the highest daily outflow Q measurement (286×10^3 m^3 d^{-1}) and daily DP mass export (116 kg) during this study. This immense volume of water that drained from the ISW in a 1-d period was equivalent to almost ten times its initial storage capacity.

It was difficult to ascribe a total quantity of DP exported from the ISW due to Hurricane Floyd because the wetland's outflow hydrology still showed the effects from Hurricane Dennis. During September, it was estimated that about 2.5 million m^3 of water discharged from the ISW promoted extremes in daily DP mass discharge. For example, on 8 September, $105 \times 10^3\ m^3\ d^{-1}$ of water and 34 kg of DP were discharged. But 1 wk afterward, $286 \times 10^3\ m^3\ d^{-1}$ of water and 116 kg of DP were exported over 1 d. If the 1-d value of 116 kg DP mass export is used to gauge the magnitude of this storm, then it represents 7% of the total DP mass load of 1688 kg exported from January to October 1999.

Hurricane Irene was the last hurricane reported in Duplin Co. during 1999. Hurricane Irene occurred approximately 1 mo after Hurricane Floyd and delivered less precipitation (48 mm). The same pattern of high outflows accompanied by heightened DP mass export from the ISW occurred after Hurricane Irene. For comparison, 1 d before Irene deposited its precipitation, Q was $110 \times 10^3\ m^3\ d^{-1}$ with a discharge of 26.5 kg of DP. Two days after Irene's precipitation ceased, Q from the ISW was between 120 and $200 \times 10^3\ m^3\ d^{-1}$, with an export of 147 kg of DP. This DP export mass represents 29% of the monthly DP mass exported (509 kg) for October. It was determined that almost 2.8 million m^3 of water passed through the ISW from 1–24 October; that translates to the ISW being flushed 97-fold with equivalent volumes of water. The study was terminated shortly after Hurricane Irene. On the termination day, the hydrologic aftereffects were still measurable because Q and DP mass export were $107 \times 10^3\ m^3\ d^{-1}$ and 10.6 kg, respectively.

The most DP exported and the highest cumulative outflows occurred in 1999 as a result of three Hurricanes-Dennis, Floyd, and Irene. Although some equipment damage caused episodes of missing sample collection, the best estimate of collective DP mass exported from the ISW as a result of Hurricanes Floyd and Irene was 1119 kg, which is over 66% of the total DP mass exported from the ISW from January to October.

Storm Influence on Dissolved Phosphorus Export Estimates

The annual cumulative DP mass and Q released from the ISW are shown in Fig. 4. The cumulative curves for DP mass export increased between 1996 and 1999, which is consistent with the significant differences between the four slope values (Table 2). On the other hand, the curves for cumulative Q appear to increase; however, the 1996 and 1997 curves cross one another multiple times. Although the slopes for the cumulative Q values are significantly different, they do not increase in magnitude between 1996 and 1999 (Table 2). Plotting the cumulative curves and comparing the slopes showed that DP mass and Q released from the ISW were influenced by year of study.

The most DP mass and Q released from the ISW occurred in 1999. Both the cumulative DP mass export and Q curves increased substantially after July as a result of Hurricanes Dennis, Floyd, and Irene. In fact, the curves were more exponential (r^2 between 0.98 and 0.99, $P < 0.0001$) than linear (r^2 between 0.71 and 0.74, $P < 0.001$ and 0.002). The exponential increase in cumulative DP mass export and Q demonstrates the catastrophic effects of three successive hurricanes on the ISW outflow hydrology and DP storage.

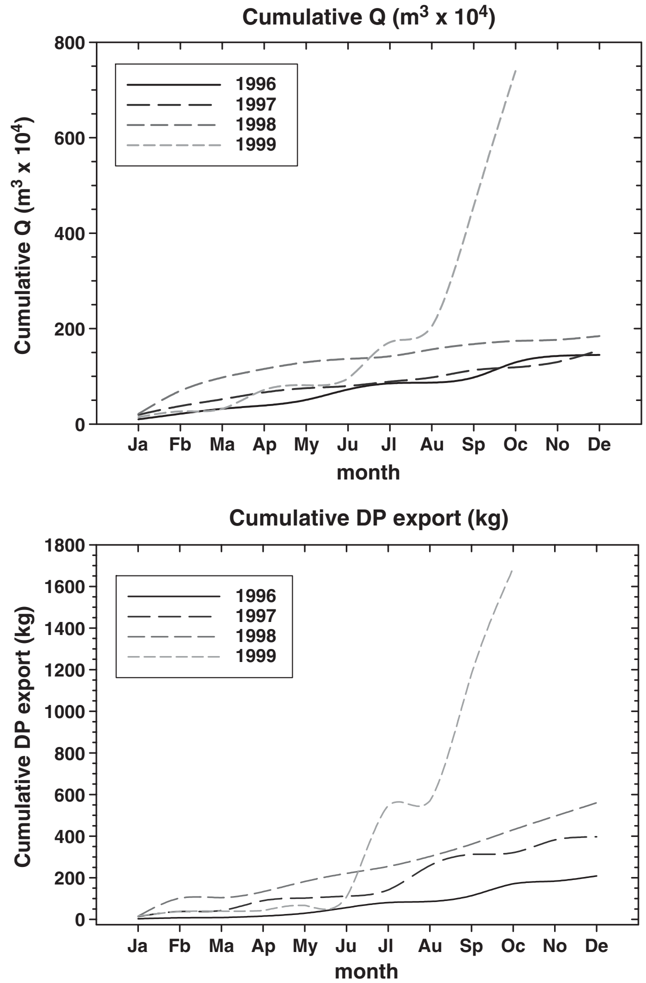

Fig. 4. Annual cumulative dissolved phosphorus (DP) mass exported and Q from the in-stream wetland.

One objective of this study was to identify particular storm characteristics that would correlate with DP release from the ISW. A Pearson product moment correlation test used on variables in Table 1 revealed that the only significant relationship occurred between the monthly DP mass export and Q values ($r^2 = 0.9$, $P <$

Table 2. Variables obtained after fitting linear regression between the month of study with both the annual cumulative dissolved phosphorus (DP) mass export and the Q from the in-stream wetland.

Parameter	Year	β†	Y_{int}	R^2	P
DP mass (kg)	1996	19.81a	−48.31	0.93	<0.001
	1997	38.02b	−62.96	0.95	<0.001
	1998	46.71c	−40.11	0.97	<0.001
	1999	165.11d	−479.01	0.74	0.001
Q (m^3)	1996	12.8×10^4a	-7.5×10^4	0.98	<0.0001
	1997	10.8×10^4b	15.7×10^4	0.98	<0.0001
	1998	12.7×10^4c	48.2×10^4	0.89	<0.0001
	1999	64.9×10^4d	-16.7×10^5	0.71	<0.002

† Slope values followed by a different letter are significantly different at $P < 0.05$.

0.001). The variability between these two parameters was determined through linear regression analyses by plotting the monthly DP export mass vs. monthly Q value in which that storm occurred (Fig. 5). This analysis revealed that a significant positive relationship ($P <$ 0.001) between monthly Q and DP mass export exists; it accounts for 81% of the variability in DP mass export. This is an important finding because it corroborates the common theme reported in this study; in that heightened DP releases from the ISW were due to Q value increases. The significant relationship between these variables provides an opportunity to estimate DP releases as a function of Q. For example, for each 500 $m^3 \times 10^3$ increase in Q, a corresponding release of 100 kg of DP will occur. This implies that water quality in downstream ecosystems is dependent on the ISW's ability to retain P; otherwise, storms that cause an increase in Q releases will concomitantly bring about the liberation of more DP.

In this study, there were repeated examples of storm events (i.e., FMS, etc.) that caused more DP mass release from the ISW compared with some TS and hurricanes. To conceptualize this effect, the mass of DP exported per month of storm was regressed using a hyperbolic model with this mass value expressed as a percentage of the annual total DP mass load (Fig. 6). The hyperbolic model was shown to fit the data very well with both a high r^2 (0.74) and significant P value (0.001). The graph shows that the three TS (1, 2, and 3) along with the two FMS contributed more to the percentage of annual total DP mass released than Hurricanes Bertha and Bonnie (Fig. 6). On the far side of the scale, Hurricanes Floyd and Irene caused the release of the most DP and ensuing percentage of the annual total DP mass export from the ISW. These results confirm that FMS and TS can have as much or even a larger influence on DP release from coastal wetlands compared with some single, less frequent hurricane events.

Phosphorus Storage within the In-Stream Wetland

Phosphorus associated with sediments represents the major P storage pool in coastal wetlands (Richardson,

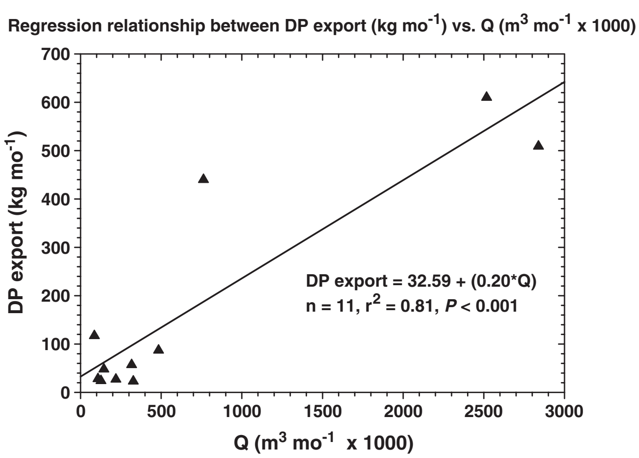

Fig. 5. Linear regression between Q and dissolved phosphorus (DP) mass exported from the in-stream wetland (n = 11).

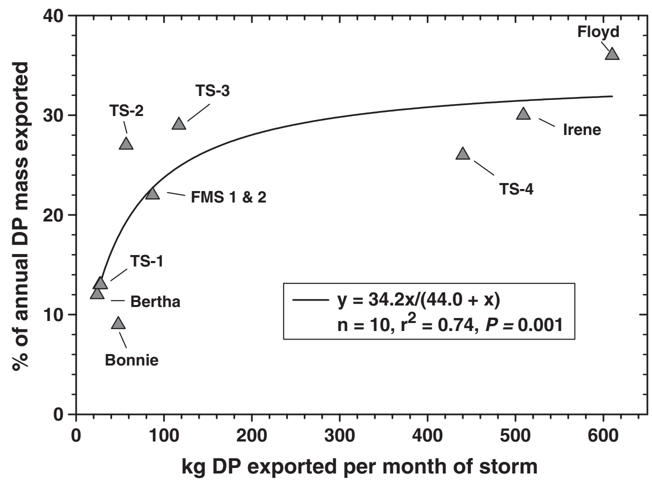

Fig. 6. Relationship between dissolved phosphorus (DP) mass export per month and the percentage of annual DP mass exported.

1999). Therefore, examining relative changes in P concentrations associated with sediments would provide a snapshot of variations in P storage. This was accomplished by measuring water column and sediment pore water DP concentrations using passive samplers (peepers) at three locations in the ISW, in sediments below the beaver dam (Fig. 2), and by sediment TP concentrations near these same locations (Table 3).

At both inlet locations, there were usually <20 μg L^{-1} of DP in the water column; however, there were sizeable concentrations measured within the sediment pore water (80 to 1400 μg L^{-1}, Fig. 7). In 1997, the sediment pore water DP concentration at the west inlet was between three and fourfold higher than at the east inlet. From 1997 to 1998, however, these DP concentrations declined at both stream inlets. The decline is probably attributable to a combination of P flushing activity from the two unnamed storms in February 1998 as well as from Hurricane Bonnie, which occurred shortly before peeper installation. While the sediment pore water DP concentration at the west inlet declined to low levels (<20 μg L^{-1}), DP concentrations at the east inlet remained between 60 and to 100 μg L^{-1}. Because the water column DP concentrations at both the west and east inlets are lower than in the sediment pore water, the concentration gradient would cause DP movement across the sediment water column interface resulting in DP transfer into the water column.

The sediment TP concentration between 1997 and 1999 at the west inlet declined from 53 to 15 mg kg^{-1} (Table 3) implying that P was removed from this area of the ISW. A sizeable decline of almost 50% in the sediment TP concentration also occurred at the east inlet

Table 3. Sediment total phosphorus (TP) concentrations.

Locations	1997	1998	1999
		TP, mg kg^{-1}	
East inlet	72	38	122
West inlet	53	41	15
Midpoint	687	744	133
Outlet	253	141	75

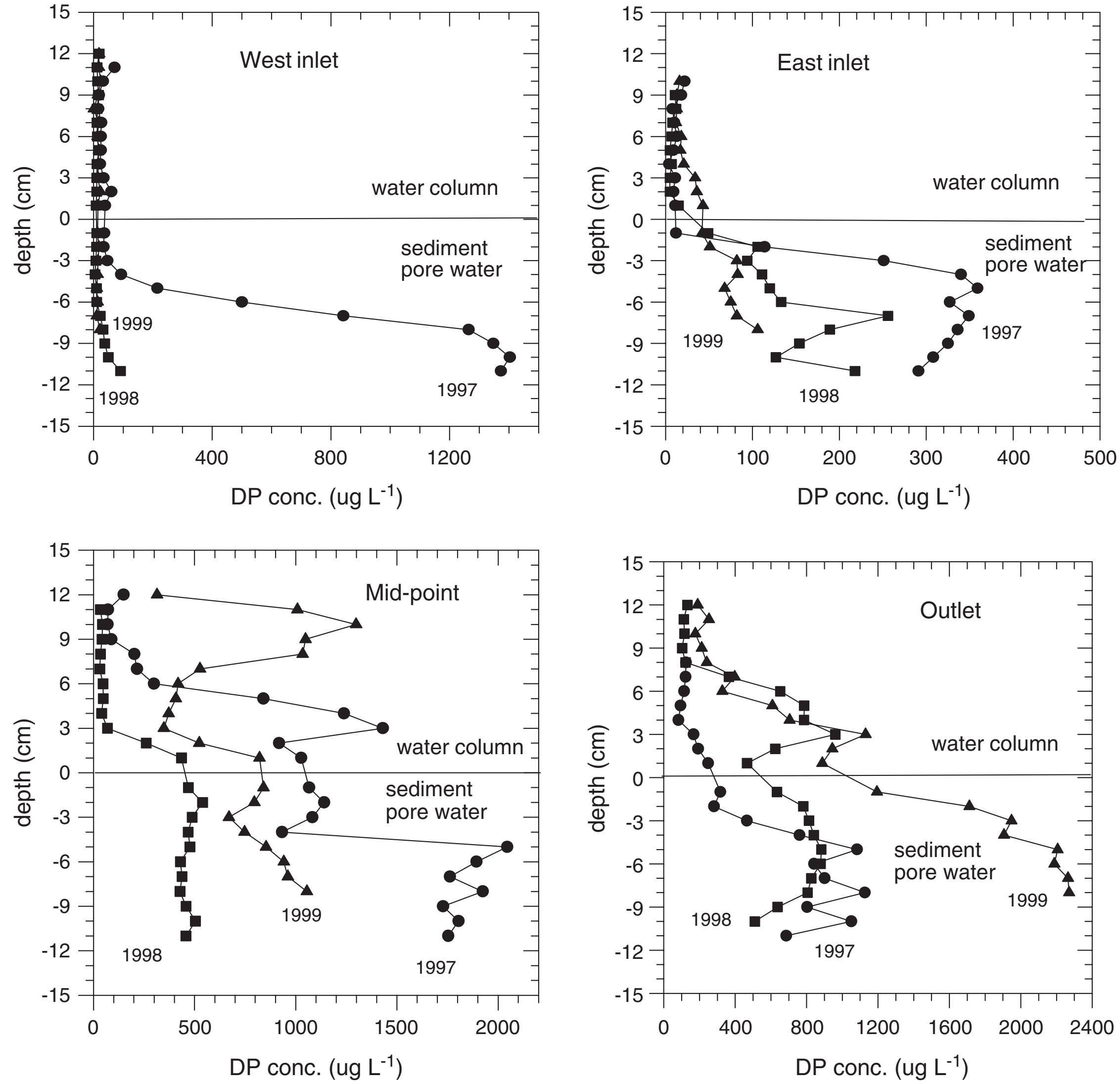

Fig. 7. Dissolved phosphorus (DP) concentrations in the sediment pore water and water column measured at four locations during 1997, 1998, and 1999.

between 1997 and 1998. By 1999, however, the sediment TP concentration increased to 122 mg kg^{-1}. The increase in sediment TP at this location is probably due to stream activity causing relocation of sediment enriched P from upstream riparian sources and/or P leakage from a nearby retired swine lagoon. This explanation is plausible because the sediments were sampled about 1 to 2 mo after TS-4 and Hurricane Dennis.

The magnitude of P concentrations in the P storage pools within this ISW was illustrated by measuring sediment pore water and TP concentrations at the midpoint within the ISW (Fig. 7, Table 3). At the midpoint location, sediment pore water DP concentrations ranged between 500 and 2200 μg L^{-1}. It is not atypical to measure wetland sediment pore water DP concentrations in excess of 1000 μg L^{-1}, particularly if the wetland was formerly agricultural land or received treated animal waste effluent (Reddy et al., 1999). The DP concentrations were higher in 1997 and declined in 1998 and 1999. Dissolved phosphorus upward and downward movement across the sediment water interface would be expected because of the shifting concentration gradients during these 3 yr. In 1997 and 1998, however, the movement was most probably upward because the maximum sediment pore water concentration was greater than the water column. This explains why some of the highest water column DP concentrations (between 1000 and 1300 μg L^{-1}) were measured in 1999 at the midpoint.

The highest sediment TP concentrations were measured at the midpoint in 1997 and 1998 (Table 3). By 1999, the sediment TP concentration at the midpoint declined by 82% relative to the 1998 measured TP concentration. Because the sediments in 1999 were sampled on 1 September, the large relative decline is due to high DP mass export during the July and August storm activity (TS-4 and Hurricane Dennis).

Sediment pore water DP concentrations at the ISW outlet between 1997 and 1998 ranged from 300 to 1100 μg L^{-1} (Fig. 7). Upward DP transfer across the sediment water interface would explain the large DP concentrations (between 100 and 1000 μg L^{-1}) measured in the water column. Sediment pore water DP concentrations at the ISW outlet increased significantly during 1999 compared with values measured in 1997 and 1998. The DP concentrations in sediment pore water at the outlet were as high as 2300 μg L^{-1}. This finding corroborates that DP was moved out of the ISW and enriched the sediment pore water fraction at the outlet. The large DP efflux from the ISW was in response to perturbation from TS-4 and Hurricane Dennis.

Sediment TP concentrations were lower at the outlet of the ISW relative to the midpoint (Table 3). Between 1997 and 1999, there was a 70% decline in sediment TP concentrations, suggesting that sediment P transferred out of the ISW did not accrete to substantial levels at the outlet. The relatively high Q during storm events probably caused stream currents to transport sediment P further down the stream continuum.

CONCLUSIONS

The ability of wetlands to retain P makes them an important landscape feature that influences water quality. Their ability to retain P, however, can be overwhelmed through hydrologic disturbances caused by both intensive precipitation totals and flooding associated with storms. High amounts of inflowing water in excess of the storage capacity of wetlands can create strong currents and turbulence that stir up DP as well as sediment-bound P, resulting in accelerated P releases with outflows. This study examined storm event characteristics on DP releases from an animal waste impacted Coastal Plain ISW and evaluated shifts in P storage pools (sediment pore water and sediment TP concentrations) that would account for potential DP releases. Results from this study showed that this ISW did release significant amounts of both DP and sediment TP after storm events. Storms, however, were found to differ greatly in their ability to accelerate P releases. Turbulence from some storm events like Hurricanes Bertha and Bonnie caused the release of <50 kg DP, while TS-2 promoted the release of 57 kg DP. The relationship showing the effects of each storm on the percentage of annual total DP mass exported supports the statement that a FMS and some TS can cause more DP export from this ISW than do single hurricane events. Regression analyses showed that variations in DP mass load released from the ISW was linked to Q differences. Storms that cause heightened Q values result in severe flushing inside the ISW and more DP export.

Successive hurricanes delivering high amounts of precipitation in a short time period were found to have a dramatic effect on DP releases from this ISW. Hurricanes Dennis, Floyd, and Irene collectively deposited record precipitation totals and exponentially increased the ISW discharge volumes. These large outflows greatly disturbed the P storage process resulting in almost 1119 kg of DP discharged, which represented 66% of the total DP released (January to October). Examining P concentrations associated with sediments revealed that major shifts in P storage pools within the ISW occurred as a result of storm activities. Dissolved phosphorus concentrations in sediment pore water and sediment TP concentrations decreased within the ISW during this study. We conclude that not all hurricane events caused significant amounts of DP release from this ISW, however; multiple hurricanes in close succession can appreciably increase DP export loads.

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